BREAKUP OF LIQUID STREAMS AT HIGH PRESSURES

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SUMMARY/OVERVIEW:
A theoretical and computational study of the break-up of injected liquid streams at high pressure by stress-induced cavitation is the research subject. The breakup criteria by stresses differs greatly from the traditional criterion in which a fluid cavitates at places and times at which the local pressure falls below the vapor pressure. Rather, cavitation occurs where the tensile stress exceeds the liquid breaking strength. The hydrodynamic stability and subsequent breakup of these liquid streams will be examined using viscous-potential-flow analysis and the direct numerical simulation of the viscous-fluid motions. The deformation of free surfaces and the fields of principal stresses are monitored to determine places and times at which the liquid is at risk to breakup.

TECHNICAL DISCUSSION:
This program just began in May, 2006. Our new approaches to the analysis of atomization are especially appropriate to systems operating at high pressures and high temperatures which cannot be explained by classical models that require low pressure; rupture can be induced at high pressure by viscous stresses. A cohesive, analytical approach is needed for the nonlinear fluid dynamics and free surface deformation, leading to the identification of critical conditions for stress-induced-cavitation, to provide engineers with a predictive capability and the understanding how liquid stream breakup is affected by various factors under the control of the designer.

Major issues which should enter into the study of breakup at high pressures are (1) determination of the regions in the round, converging orifice at risk to stress-induced cavitation; (2) hydrodynamic stability including the nonlinear dynamics for Rayleigh-Taylor (RT), Kelvin-Helmholtz (KH) and capillary instabilities; (3) viscosity and vorticity; and (4) breaking the liquid continuum. Different mechanisms which can lead to breaking and rupture of the liquid continuum are cavitation, capillary collapse, and disjoining pressures associated with molecular attractions. For the formation of sprays or droplet streams with super-micron diameters, stress-induced cavitation is the strongest candidate.

It is widely understood[1] that, for diesel injection, disintegration of the continuum begins internally in the nozzle and a continuous liquid core surrounded by fragmented fluid exits from the injector nozzle. Cavitation can play a major role in the disintegration process. The flow near the orifice walls accelerates more than the core flow resulting in lower pressure near the walls. Therefore, the region near the walls is preferred for cavitation

and stress-induced cavitation can occur around the liquid perimeter near the wall while the liquid still is inside the orifice. This fragments the outer shell but leaves an intact core. The bubble growth immediately following the fracture perturbs the core flow inducing Kelvin-Helmholtz (KH) capillary waves. These short, nonlinear surface waves have peaks that emerge as protrusions from the surface of the liquid core flow and might rupture, forming liquid fragments.

Experimental evidence[1] indicates that cavitation or cavitation in combination with other mechanisms is the most likely candidate for liquid-stream breakup at high flow velocities. Here an examination of the axisymmetric flow within the converging orifice is required. We will consider sub-millimeter-diameter dimensions, say O(100μm), for the orifice and velocities of O(10-100 m/s). For the liquids considered, this will yield Reynolds numbers in the high laminar to transitional regimes. Unsteady solutions will be allowed so as to capture flow instabilities. The cavitation number should be determined throughout the internal and near-exit flow, indicating the zones for likely cavitation. The principal viscous stresses (not merely thermodynamic pressure) should be computed. Two types of analysis can be made: numerical solutions of the Navier-Stokes equation and viscous potential flow. Analyses of stress-induced cavitation have been performed by Joseph and co-workers for flow through a planar aperture[2] and axisymmetric flow over a sphere.[3]

We expect cavitation at places where the tension exceeds the cavitation threshold p_c. The calculation would compare points of minimum pressure with points of maximum tension. Our main interest will be on axisymmetric and three-dimensional flows. In the study of Padrino et al.,[3] the problem of stress-induced cavitation in the flow of a viscous fluid over a sphere is studied in the Stokes flow limit, by viscous potential flow and by direct simulation of the Navier-Stokes equation.

Three criteria for breakup can be applied in the theory of stress-induced cavitation. All three are framed in terms of principal stresses in the convention $T_{11} \geq T_{33} \geq T_{22}$. In the classical theory of cavitation, the viscous part of the stress tensor is not considered and the threshold pressure p_c is the vapor pressure p_v. So, $\boldsymbol{T} + p_c\boldsymbol{1} = (-p + p_v)\boldsymbol{1}$. The classical theory assumes that the cavitation threshold is given by the negative of the average stress, called the pressure. The fluid cannot average its stresses; it sees only principal stresses and when the actual state of stress is considered there is at least one stress which is more compressive and another which is more tensile than the average stress. The most conservative criterion is the one which requires that the most compressive stress is larger than the vapor pressure; if T_{22} is the most compressive and T_{11} is the most tensile stress, then, if $T_{22} + p_c > 0$ for cavitation, it will surely be true that $-p + p_c > 0$ and $T_{11} + p_c > 0$. We may consider the possibility that a cavity will form if all stresses are in tension; it will not form if all stress are in compression. The case in which the stresses have different signs is ambiguous; a cavity will open in tension but close in compression. This is the situation for the classical theory when the pressure is close to the vapor pressure and the motion produces viscous stresses with different signs. The maximum tension theory, which perhaps embodies the statement that liquids which are

not specially prepared will cavitate when they pass into tension, can be expressed by the condition that, if T_{11} is the maximum of the three principal stresses, then $T_{11} + p_v > 0$ where $K = \frac{p_\infty - p_c}{\frac{1}{2}\rho U^2}$ is the cavitation number. Suppose now that T_{11} is the largest of the three principal values of stress. Then the locus of the cavitation threshold is given by $T_{11} + p_c = 0$. The threshold condition gives an isoline inside of which bubbles will nucleate. Figure 1 gives Navier-Stokes results for Re = 100.

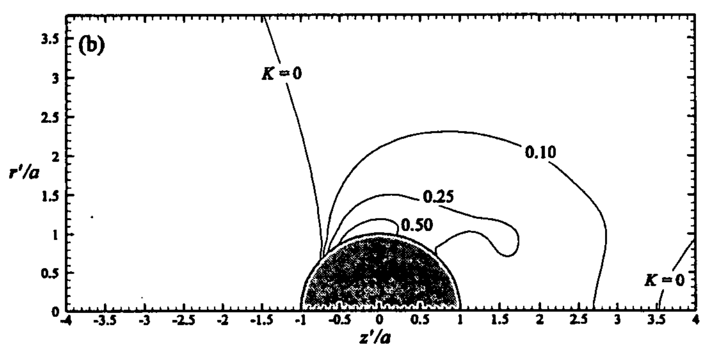

Figure 1. The cavitation threshold curves on which $T_{11} + p_c = 0$ for different values of the cavitation number K. $Re = 100$. Cavitation occurs in the region enclosed by the curve on which $T_{11} + p_c = 0$.

Bubbles will nucleate and coalesce in the regions inside the isolines for cavitation. This leads to bubbly flows for which interface tracking is required. We do not plan to follow the calculation into the bubbly regimes but the motion and orientation of these bubbles will be controlled by the state of stress at the interface and the bubbles will tend to elongate in the direction of maximum tension.

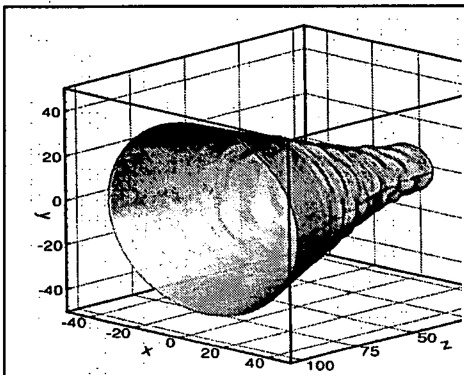

Figure 2. Spatially developing nonlinear sinuous 3D instability on swirling conical liquid sheet.[4]

The existing literature on liquid-stream stability (and straining under unstable conditions) addresses collectively dilational and sinuous capillary and KH/capillary waves, temporal and spatial (and absolute and convective) instabilities, and linear and nonlinear behavior. The focus of this portion of the research will be on nonlinear behavior leading to breakup. However, linear analysis of stability is essential to establish the domain of parameters in which instability leading to collapse is expected, to identify the types of instability, to determine the wave lengths which grow most rapidly, to establish the cut-off values between stability and instability, to determine if there are neutral curves establishing conditions under which the gas streams are always stable and to identify how all these important linear functionals of the solution depend on the control parameters of the problem. Figures 2 and 3 show the results of a calculation for a nonlinear sinuous wave on a swirling "conical" sheet that is modulated at the injection plane.[4] Clearly, a complex pattern of "spotty" thinning can occur; this pattern would not be predicted as well by any linear theory. These regions of thinning again are the candidate locations for rupture. Large gradients occur in the neighborhoods of these locations so that, for better accuracy,

viscous effects should be included in the calculations. The results from these four figures give a conclusion that also applies for other configurations: *nonlinear and viscous effects must be considered in a theory of liquid-stream rupture.*

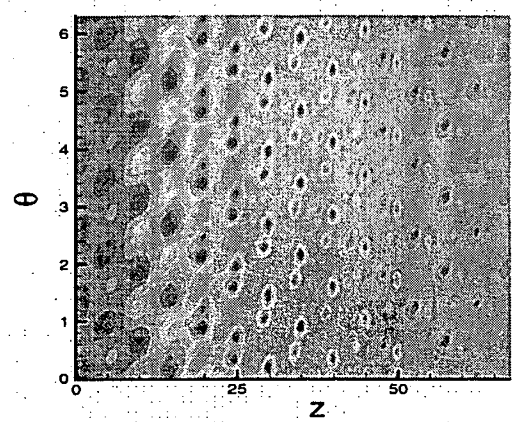

Figure 3. Instantaneous film thickness as a function of position on surface.[4]

Emphasis in the proposed research will be on round jets operating at high pressures, high temperatures, and high flow velocities. Orifice pressure drops as high as 100 bars will be considered. Practical injectors can have larger drops but, in this first study, we plan to avoid developed turbulent flows. Decane will be used as a surrogate fuel that is representative of the relevant volatility and viscosity range. Orifice diameters will be in the sub-millimeter range of practical interest. Summary descriptions of the tasks follow. First, the internal orifice flow of viscous fluids will be analyzed to identify zones of flow at risk to stress-induced cavitation. A variety of analytical techniques will be employed emphasizing extended analyses of the irrotational flows of viscous fluids spot checked by exact numerical simulations of flows governed by the Navier-Stokes equations. The amounts of fragmented fluid at the orifice exit and the flow in the intact core will be estimated. The exit-velocity profile for the intact core will also be determined. The hydrodynamic stability of the intact core will be studied by the imposition of modulated waves at the exit. Viscosity effects and surface tension will be included in the analysis. The cavitation number will be resolved locally at each point in the core continuously with time to identify location of rupture. Rupture of ligaments from the core surface due to both stress-induced cavitation and capillary collapse can be considered. The dynamic evolution of the core surface will be determined using numerical simulation with surface-tracking techniques. Two- and three-dimensional KH/capillary instabilities will be computed.

[1]Reitz, R.D. and Bracco, F.V., "Mechanism of Atomization of a Liquid Jet," *Physics of Fluids,* Vol. 25, 1982, pp. 1730-42.

[2]Funada, T., Wang, J., and Joseph, D. D., Viscous Potential Flow Analysis of Stress Induced Cavitation of Aperture Flow." *Atomization & Sprays,* Vol. 16, No. 7, 2006, in press.

[3]Padrino, J.C., Joseph, D. D., Funada, T., Wang, J., and Sirignano, W. A., "Stress Induced Cavitation for the Streaming Motion of a Viscous Liquid Past a Sphere," 2006. Submitted.

[4]Mehring, C. and Sirignano, W.A., "Capillary Stability of Modulated Swirling Liquid Sheets," *Atomization & Sprays* 14, 2004, pp. 397-436.